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Detection of Coronary Artery Stenosis With Whole-Heart Coronary Magnetic Resonance Angiography

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OBJECTIVES We sought to determine the diagnostic performance of whole-heart coronary magnetic resonance (MR) angiography for detecting significant coronary artery disease.

BACKGROUND The accuracy of whole-heart coronary MR angiography has not been determined in a large number of patients.

METHODS Three-dimensional coronary MR angiograms covering the entire heart were obtained during free breathing in 131 patients. Images were acquired during a patient-specific time window in the cardiac cycle with minimal motion of the coronary artery. Significant coronary artery disease was defined on X-ray coronary angiography as a diameter reduction of ≥50% in coronary arteries with a reference diameter of ≥2 mm.

RESULTS The acquisition of MR angiography was completed in 113 (86%) of 131 patients, with an imaging time averaged at 12.9 ± 4.3 min. On a patient-based analysis, the sensitivity, specificity, positive and negative predictive value, and accuracy of MR angiography were 82% (95% confidence interval [CI] 69% to 91%), 90% (95% CI 79% to 96%), 88% (95% CI 74% to 95%), 86% (95% CI 75% to 93%), and 87% (95% CI 79% to 92%), respectively. These values in the individual segments were 78% (95% CI 68% to 85%), 96% (95% CI 95% to 97%), 69% (95% CI 60% to 77%), 98% (95% CI 96% to 98%), and 94% (95% CI 96% to 96%).

CONCLUSIONS Whole-heart coronary MR angiography allows for noninvasive detection of significant narrowing in coronary arterial segments with a diameter of ≥2 mm with moderate sensitivity and high specificity. (J Am Coll Cardiol 2006;48:1946–50) © 2006 by the American College of Cardiology Foundation

A previous multicenter study demonstrated that 3-dimensional respiratory-gated coronary magnetic resonance (MR) angiography reliably identifies patients with left main coronary artery or 3-vessel disease (1). However, coronary MR angiography remains time-consuming because only a limited portion of the entire coronary arteries is imaged for each double-oblique acquisition. Whole-heart coronary MR angiography using a

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free-breathing, 3-dimensional steady-state free precession sequence recently has been introduced as a method that can provide visualization of all 3 major coronary arteries (2–4). With this method, one can visualize long segments of major coronary vessels with reduced total examination time. However, the accuracy of whole-heart coronary MR angiography for detecting coronary stenoses has not been determined in a large number of patients. Consequently, we conducted a prospective study to investigate the diagnostic value of this method for the detection of obstructive coronary artery disease.

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METHODS

Patients. During a period of 14 months from January 2004, 145 subjects were consecutively recruited from patients with suspected coronary artery disease who were scheduled for elective X-ray coronary angiography. Exclusion criteria included general contraindications to MR examination, unstable angina, atrial fibrillation, and previous coronary artery bypass graft surgery. Fourteen patients were excluded based on these exclusion criteria. Thus, the study population comprised 131 patients (115 men and 16 women; mean age, 66.2 ± 10.7 years). The study protocol was approved by the institutional review board of Matsusaka Central Hospital, and all subjects gave written informed consent.

Magnetic resonance data acquisition. Magnetic resonance images were acquired with a 1.5-T MR imager (Intera, Philips Medical Systems, Best, the Netherlands) using 5-element cardiac coils. Five milligrams of isosorbide dinitrate was administered sublingually before the MR study. Initial survey images to determine position of the heart and diaphragm and reference images to evaluate the individual coil sensitivities for parallel imaging acquisition were obtained while the patient was free breathing. To monitor motion of the right coronary artery (RCA), transaxial cine MR images were acquired with a steady-state sequence while the patient was free breathing (repetition

Abbreviations and Acronyms

MR = magnetic resonance
RCA = right coronary artery

time = 2.6 ms, echo time = 1.3 ms, flip angle = 60°, field of view = 320 × 320 × 120 mm, acquisition matrix = 128 × 128, cardiac phases = 50, SENSE factor = 3.0, imaging time = 3 s). In contrast to previous studies (1–5), a patient-specific acquisition window was set either during systole or during diastole, depending on the phase of minimal motion of the RCA. Magnetic resonance angiograms were acquired during diastole in 83 patients (averaged heart rate = 65.1 ± 9.4 beats/min, delay after R-wave trigger = 627 ± 64 ms, acquisition window = 152 ± 67 ms), and during systole in 48 patients (averaged heart rate = 83.2 ± 9.5 beats/min, delay after R-wave trigger =259 ± 39 ms, acquisition window = 98 ± 26 ms). Whole-heart coronary MR angiography was obtained while patients were free breathing, with the use of a 3-dimensional, segmented steady-state free precession sequence with T2 preparation and radial k-space sampling (repetition time = 4.6 ms, echo time = 2.3 ms, flip angle = 90°, excitations per cardiac cycle = 20 to 50, SENSE factor = 2.0, navigator gating window of ±2.5 mm, no drift correction, field of view = 280 × 280 × 120 mm, acquisition matrices = 256 × 256 × 80, reconstruction matrices = 512 × 512 × 160) (6).

Magnetic resonance data analysis. Magnetic resonance images were transferred to an image analysis workstation (Virtual Place Advance, Aze, Tokyo, Japan). Axial images and curved multiplanar reformatted reconstructions were evaluated by 2 observers. Image quality was classified on a 4-point scale (1 = poor, 2 = moderate, 3 = good, and 4 = excellent). The coronary arteries were visually screened for the significant narrowing (≥50% diameter reduction) of the lumen. Disagreement between 2 observers was settled by a consensus reading. The in-stent coronary lumen was not included in the analysis. To evaluate the influence of heart rate on image quality, the patient cohort was subdivided into 2 groups: group 1 with heart rate <70 beats/min (n = 51, mean heart rate 60.7 ± 6.0 beats/min, ranging from 45 to 69 beats/min); group 2 with heart rate ≥70 beats/min (n = 62, mean heart rate 81.7 ± 9.5 beats/min, ranging from 70 to 115 beats/min).

X-ray coronary angiography. Conventional X-ray coronary angiography was evaluated by a separate blinded reviewer. Significant coronary arterial stenosis was defined as a luminal diameter reduction of ≥50%. Lesions with a reference diameter of 2 mm or more on X-ray coronary angiography were included when determining the diagnostic value of coronary MR angiography.

Statistical analysis. The averaged image quality score was determined in the segments with minimal diameter of ≥2.0 mm on X-ray coronary angiography. The diagnostic accuracy of MR angiography was determined for the lesions with reference diameter of ≥2.0 mm on X-ray coronary angiography regardless of the image quality of MR angiography in patients who completed MR acquisition. Continuous data are expressed as mean value ± standard deviation. Unpaired *t* tests were performed to evaluate the difference between groups. We considered p values of <0.05 to be statistically significant.

RESULTS

The patient characteristics are summarized in Table 1. Acquisition of whole-heart coronary MR angiography was completed in 113 (86%) of 131 patients, with an imaging time averaged at 12.9 ± 4.3 min, ranging from 5.8 to 28.8 min. Eighteen patients without successful MR angiographic acquisition demonstrated an irregular breathing pattern or drift of the diaphragm position during MR data acquisition. Low navigator efficiency of less than 20% generally indi-

Table 1. Characteristics of the Patients

Characteristics	All Patients Who Underwent Coronary MR Angiography (n = 131)	Patients With Successful Acquisition of Coronary MR Angiography (n = 113)
Male/female	115/16	98/15
Age (yrs)	66.2 ± 10.7	66.1 ± 10.7
Range	39–85	39–85
Heart rate (beats/min)	71.8 ± 12.9	72.2 ± 13.2
Range	45–115	45–115
Body weight (kg)	63.4 ± 10.3	63.1 ± 10.1
Prior myocardial infarction, n (%)	42 (32%)	36 (32%)
History of systemic hypertension, n (%)	83 (63%)	69 (61%)
Current or prior cigarette smoking, n (%)	55 (42%)	46 (41%)
Cholesterol >200 mg/dl, n (%)	71 (54%)	60 (53%)
Diabetes, n (%)	42 (32%)	34 (30%)
Coronary stent	22 (17%)	19 (17%)
Stenosis on coronary angiography, n (%)	61 (47%)	51 (45%)
One-vessel disease	38	34
Two-vessel disease	12	9
Three-vessel disease	11	8

MR = magnetic resonance.

Table 2. Image Quality, Sensitivity, and Specificity of the Whole-Heart Coronary Magnetic Resonance Angiography in the Individual Segments

	No. of Segments ≥2.0 mm	Image Quality in All Patients	p Value*	Image Quality in 51 Patients With Heart Rate of <70 Beats/min	Image Quality in 62 Patients With Heart Rate of ≥70 Beats/min	p Value†	Sensitivity (%)	Specificity (%)
RCA								
Proximal	113	3.8 ± 0.6		3.9 ± 0.4	3.7 ± 0.7	0.08	83 (36–99)	98 (93–100)
Mid	113	3.7 ± 0.6	0.71	3.8 ± 0.5	3.6 ± 0.7	0.10	92 (62–100)	95 (88–98)
Distal and branches	106	3.7 ± 0.6	0.40	3.7 ± 0.6	3.6 ± 0.6	0.36	80 (51–95)	96 (89–99)
LM	113	3.7 ± 0.6		3.8 ± 0.4	3.5 ± 0.8	0.07	NA	98 (93–100)
LAD								
Proximal	113	3.7 ± 0.6		3.8 ± 0.5	3.6 ± 0.7	0.11	82 (56–95)	96 (89–99)
Mid	112	3.7 ± 0.6	0.68	3.8 ± 0.5	3.7 ± 0.6	0.40	81 (54–95)	97 (90–99)
Distal	58	3.8 ± 0.4	0.39	3.7 ± 0.4	3.8 ± 0.4	0.63	67 (13–98)	96 (86–99)
Diagonal branches	28	3.5 ± 0.7	0.14	3.5 ± 0.7	3.5 ± 0.8	0.82	67 (13–98)	96 (78–100)
LCX								
Proximal	110	3.5 ± 0.7		3.7 ± 0.6	3.4 ± 0.8	0.08	40 (7–83)	96 (90–99)
Distal	70	3.6 ± 0.7	0.32	3.7 ± 0.5	3.5 ± 0.7	0.34	75 (47–92)	93 (81–98)
Marginal branches	64	3.1 ± 0.8	<0.01	3.2 ± 0.6	3.1 ± 1.0	0.50	67 (24–94)	93 (82–98)

Values in parentheses represent 95% confidence intervals. *p values represent significance of the difference compared with the image quality score in the proximal segment in each major coronary artery. †p values represent significance of the difference in image quality score between patients with heart rate of <70 beats/min and patients with heart rate of ≥70 beats/min.

LAD = left anterior descending artery; LCX = left circumflex coronary artery; LM = left main artery; RCA = right coronary artery.

cated unsuccessful acquisition of whole-heart coronary MR angiography. No significant difference in the mean heart rate was observed between the patients with and without successful MR acquisition (72.2 ± 13.2 beats/min vs. 66.2 ± 10.7 beats/min; $p = 0.17$). Table 2 summarizes the image quality score, sensitivity, and specificity of whole-heart coronary MR angiography assessed in the individual segments. Although the image quality score in marginal branches of the left circumflex artery was significantly lower than that of the proximal left circumflex artery ($p < 0.01$), no statistically significant difference was found between the proximal and distal segments in other vessels (p values ranged from 0.14 to 0.71). No significant differences were found in the image quality score between group 1 (heart rate <70 beats/min) and group 2 (heart rate ≥70 beats/min) in any segment (p values ranged from 0.07 to 0.82). Significant stenosis in the coronary artery was observed on X-ray coronary angiography in 51 (45%) of 113 patients who completed MR acquisition, and 42 (82%) of these 51 patients were correctly classified by MR as having significant stenosis (Table 3, Figs. 1 and 2). After excluding segments with stents and those with a diameter of <2 mm, 1,000 of 1,243 segments were evaluated. Coronary MR angiography demonstrated the sensitivity of 78% (95% confidence interval [CI] 68% to 85%) and specificity of 96% (95% CI 95% to 97%) on a segment-based analysis. On a patient-based analysis, the sensitivity, specificity, positive and negative predictive value, and accuracy of MR angiography were 82% (95% CI 69% to 91%), 90% (95% CI 79% to 96%), 88% (95% CI 74% to 95%), 86% (95% CI 75% to 93%), and 87% (95% CI 79% to 92%). Sixteen (94%) of 17 patients with double- or triple-vessel disease were identified by MR as having significant stenosis in at least 1 coronary artery.

DISCUSSION

In this prospective study, the accuracy of whole-heart coronary MR angiography was evaluated in 131 patients with suspected coronary artery disease. The current MR angiography protocol incorporated several improvements over those used in previous studies. First, MR angiograms were acquired on axial 3-dimensional planes that encompassed the entire heart. Second, the image acquisition window in the cardiac cycle was optimized in each patient to

Table 3. Diagnostic Accuracy of Whole-Heart Coronary Magnetic Resonance Angiography to Detect Stenoses of ≥50% in 113 Patients Who Completed Acquisition of Coronary Magnetic Resonance Data

	n	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	Accuracy (%)
Per patient	113	82 (69–91)	90 (79–96)	88 (74–95)	86 (75–93)	87 (79–92)
Per vessel	452	78 (66–86)	96 (93–97)	79 (67–87)	95 (93–97)	93 (90–95)
RCA	113	85 (65–95)	95 (88–98)	85 (65–95)	95 (88–98)	93 (86–97)
LM	113	NA	98 (93–100)	NA	100 (96–100)	98 (93–100)
LAD	113	77 (56–90)	95 (88–99)	83 (62–95)	93 (85–97)	91 (84–95)
LCX	113	70 (47–86)	93 (86–97)	73 (50–88)	92 (84–97)	89 (81–94)
Per segment	1,000	78 (68–85)	96 (95–97)	69 (60–77)	98 (96–98)	94 (93–96)

Values in parentheses represent 95% confidence intervals.

LAD = left anterior descending artery; LCX = left circumflex coronary artery; LM = left main artery; RCA = right coronary artery.

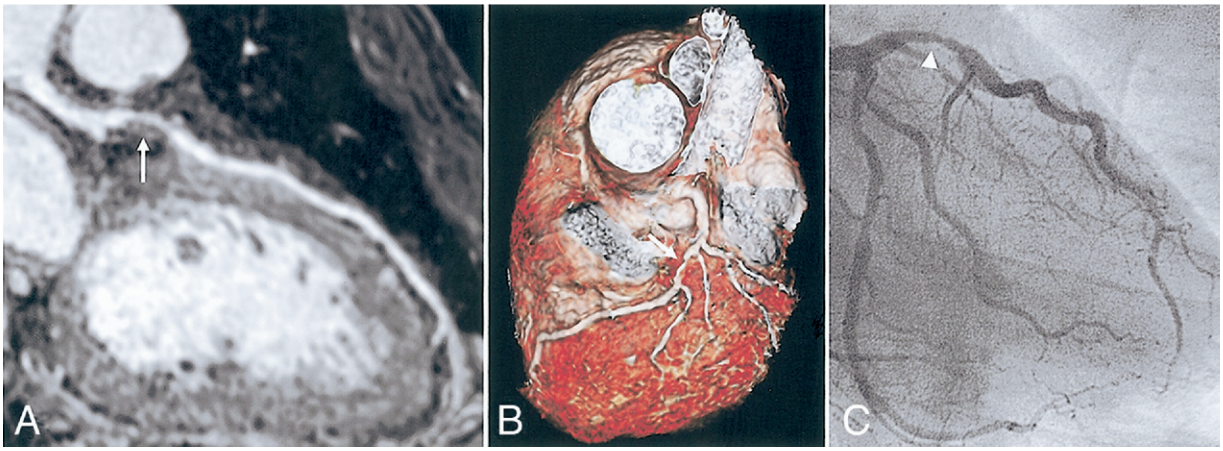

Figure 1. Visualization of a stenosis in the left anterior descending artery (LAD) with whole-heart coronary magnetic resonance angiography. **(A)** Curved multiplanar reconstruction image shows a stenosis in LAD **(white arrow)**. **(B)** Volume-rendering method demonstrates 3-dimensional view of LAD with stenosis **(white arrow)**. **(C)** X-ray coronary angiography reveals a stenosis of proximal LAD **(arrowhead)**.

minimize motion blurring caused by cardiac contraction. Using this approach, coronary stenoses with a reference diameter of ≥2 mm were detected with an accuracy of 94% for individual segments and 87% for individual patients.

Coronary MR angiography has been acquired in double-oblique 3-dimensional planes that followed the course of one of the major coronary arteries, necessitating repeated MR acquisitions to cover the entire coronary arteries (1). A steady-state, free-precession MR sequence permitted acquisition of a large 3-dimensional volume covering the entire heart without compromising the higher luminal signal of arteries (2–4). Planning of the 3-dimensional volume for whole-heart coronary MR angiography is quite simple, and considerable time gain can be obtained by eliminating 3-point planning that was required for double oblique 3-dimensional coronary MR angiography.

Prospective electrocardiographic gating has been used to correct for cardiac motion on coronary MR angiography by acquiring imaging data during mid-diastole (1–6). In a recent study that evaluated an optimal reconstruction interval for multidetector row computed tomography coronary angiography (7), good coronary arterial images were obtained by reconstructing images during mid-diastole in patients with heart rates of <70 beats/min. However, reconstructions at an earlier stage in the cardiac cycle were necessary in patients with higher heart rates. In the current study, an interval of minimal motion of the RCA was visually determined on cine MR images, resulting in the utilization of coronary MR data during diastole in 83 patients and during systole in 48 patients. The use of a patient-specific acquisition window in the cardiac cycle provided reduced motion blurring on coronary MR angiography, allowing us to obtain diagnostic coronary MR images in patients with relatively high heart rates.

In a previous multicenter study using a double oblique, 3-dimensional gradient echo sequence (1), the accuracy of coronary MR angiography in identifying a patient as having coronary artery disease was 72%. Kefer et al. (8) used a steady-state, double oblique 3-dimensional coronary MR angiography and found that MR angiography had an accuracy of 75% in detecting patients with significant

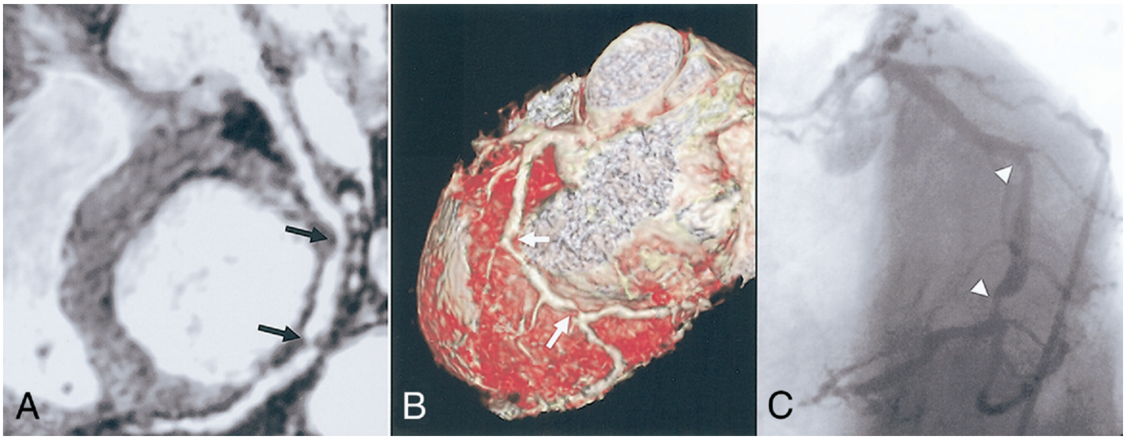

Figure 2. A patient with stenosis in the left circumflex (LCX) artery. **(A)** Curved multiplanar reconstruction demonstrates stenoses of LCX in 2 locations **(black arrows)**. **(B)** Volume rendering method shows 3-dimensional view of LCX with stenoses **(white arrows)**. **(C)** X-ray coronary angiography of the same artery confirms stenoses of LCX **(arrowhead)**.

coronary artery disease. The diagnostic accuracy observed in this study (87%) was at least comparable with the results reported in these previous studies, whereas a considerable time gain was obtained by eliminating time-consuming 3-point planning used for the double oblique, targeted volume approach.

Study limitations. Several important limitations should be acknowledged in current whole-heart coronary MR angiography. The sensitivity and negative predictive value of the current whole-heart coronary MR angiographic approach were not as good as those in recent reports that evaluated the diagnostic performance of 64-slice multidector computed tomography (9,10). Magnetic resonance image data acquisition was not successful in approximately 14% of the patients, and the diagnostic performance of MR was evaluated in the 113 patients who completed MR angiographic acquisition. Failure of MR acquisition was caused by an unstable breathing pattern or drift of the diaphragm position during scan, indicating the necessity of improving respiratory gating and respiratory motion correction before coronary MR angiography is widely used in clinical practice. Further improvements seem to be required before coronary MR angiography is widely used in the clinical setting. The present study was performed in patients with intermediate prevalence of coronary artery disease (45.1%). The findings in this study may not be directly extrapolated to the population with a lower prevalence of coronary artery disease. Although the number of patients enrolled in this single-center study was greater than those in previous studies, the number of the segments with significant luminal narrowing was not sufficient to reliably determine the sensitivity and positive predictive value in individual segments. A multicenter study is desirable to support the diagnostic value of coronary MR angiography for widespread clinical application. The patients who underwent emergency coronary angiography were not evaluated in this study. Therefore, the accuracy of coronary MR angiography in detecting acute coronary artery occlusion or stenosis needs to be clarified in further studies.

Conclusions. Whole-heart coronary MR angiography allows for noninvasive detection of significant luminal narrowing in the coronary artery with moderate sensitivity and high specificity. It should be also noted that MR acquisition was not successful in approximately 14% of the patients because of an unstable breathing pattern or drift of the diaphragm position during scan.

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